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Azimuthal Asymmetries in Hadronic Final States at HERA

M. Ahmed[a,b] and T. Gehrmann[c]

[a] *II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany*

[b] *University of the Punjab, Lahore, Pakistan*

[c] *Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*

Abstract

The distribution of hadrons produced in deeply inelastic electron–proton collisions depends on the azimuthal angle between lepton scattering plane and hadron production plane in the photon-proton centre-of-mass frame. In addition to the well known up-down asymmetry induced by the azimuthal dependence of the Born level subprocess, there is also a non-vanishing left-right asymmetry, provided the incoming electron is polarized. This asymmetry is time-reversal-odd and induced by absorptive corrections to the Born level process. We investigate the numerical magnitude of azimuthal asymmetries in semi-inclusive hadron production at HERA with particular emphasis on a possible determination of the time-reversal-odd asymmetry.

The increase in the statistical accuracy of deep inelastic scattering (DIS) data at the HERA collider will soon allow to investigate hadronic final state observables which go beyond hadron multiplicity distributions [1] and jet rates that have been studied up to now. Observables of particular interest are angular correlations between the lepton scattering plane, defined by the incoming and outgoing lepton momenta and the hadron production plane, defined by incoming proton and outgoing hadron momentum. These correlations probe the dynamics and colour flow of the underlying partonic interaction at a detailed level, such that they can be used to test the perturbative description of hadron production via partonic fragmentation. An accurate prediction of the perturbatively induced asymmetries is in particular desirable since azimuthal correlations in semi-inclusive DIS have been suggested as probes of non-perturbative effects in various places in the literature [2].

In this paper, we estimate the magnitude of the different azimuthal asymmetries for kinematical conditions at the HERA collider, using parton model expressions at leading order. Particular emphasis is put on time-reversal-odd (T-odd) asymmetries, resulting from absorptive contributions to the parton level scattering amplitudes [3]. These T-odd effects manifest in left-right asymmetries of the hadron distribution with respect to the lepton scattering plane [6, 7]. Corresponding to antisymmetric contributions to the hadronic tensor, their observation requires either the contribution from parity violating weak interactions or polarization of the initial lepton beam. Given that lepton beam polarization will soon be realized for the HERA collider experiments, both cases shall be investigated below. Perturbative T-odd effects have up to now only been studied experimentally in polarized electron-positron annihilation at SLAC [4], where the expected asymmetries [5] are however too small to be measured directly, such that only upper limits could be determined [4].

The kinematics of the semi-inclusive reaction

$$l(k) + p(p) \longrightarrow l'(k') + h(P) + X$$

are described by the following invariant variables

$$\begin{aligned} Q^2 &= -q^2 = -(k-k')^2 \;, \\ x &= \frac{Q^2}{2q\cdot p} \;, \\ z &= \frac{p\cdot P}{q\cdot p} \;, \\ \kappa^2 &= z^2\left(1 - \frac{q\cdot P}{xp\cdot P}\right) \end{aligned} \tag{1}$$

and the azimuthal angle ϕ between outgoing lepton direction and outgoing hadron direction measured in the centre-of-mass frame of virtual gauge boson and proton. The variable κ relates to the transverse momentum of the outgoing hadron in this frame by $\kappa^2 = P_T^2/Q^2$. The semi-inclusive scattering cross section can be decomposed according to the dependence on ϕ:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}\phi\mathrm{d}P_T^2} = \frac{\alpha^2\pi}{2Q^6 z}\left(A + B\cos\phi + C\cos 2\phi + D\sin\phi + E\sin 2\phi\right) \;. \tag{2}$$

Explicit parton model expressions for the coefficients A–E can be found in [6, 7], the description of charged current (CC) interactions requires the substitution $\alpha \to G_F Q^2/(\sqrt{2}\pi)$. It should be noted that the leading order contribution to A is $\mathcal{O}(1)$, corresponding to vanishing transverse momentum of the outgoing hadron. The first contribution to A yielding $\kappa \neq 0$ is $\mathcal{O}(\alpha_s)$. The leading order contributions to B and C are $\mathcal{O}(\alpha_s)$ and to D and E are $\mathcal{O}(\alpha_s^2)$.

D and E are time-reversal-odd, they are induced by absorptive one-loop corrections to the partonic scattering amplitudes. They appear in the hadronic tensor with asymmetric coefficients, which implies their vanishing for purely electromagnetic interactions with unpolarized beams. Non-vanishing T-odd asymmetries are obtained only for weak interactions or for electromagnetic interactions with a longitudinally polarized lepton beam.

In order to suppress the large $\mathcal{O}(1)$ contribution to the ϕ-independent coefficient A, it is appropriate to restrict studies of angular asymmetries to hadrons produced at non-zero p_T. To project out individual terms in (2), we define the following average asymmetries, depending on x, Q^2 and P_T:

$$
\begin{aligned}
\langle \sin(n\phi) \rangle (x, Q^2, P_T) &= \frac{\displaystyle\int \mathrm{d}z \mathrm{d}\phi \sin(n\phi) \frac{\mathrm{d}\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\phi \mathrm{d}P_T^2}}{\displaystyle\int \mathrm{d}z \mathrm{d}\phi \frac{\mathrm{d}\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\phi \mathrm{d}P_T^2}} , \\
\langle \cos(n\phi) \rangle (x, Q^2, P_T) &= \frac{\displaystyle\int \mathrm{d}z \mathrm{d}\phi \cos(n\phi) \frac{\mathrm{d}\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\phi \mathrm{d}P_T^2}}{\displaystyle\int \mathrm{d}z \mathrm{d}\phi \frac{\mathrm{d}\sigma}{\mathrm{d}x \mathrm{d}Q^2 \mathrm{d}z \mathrm{d}\phi \mathrm{d}P_T^2}} . \qquad (3)
\end{aligned}
$$

The integration over the outgoing hadron momentum z is a priori bounded only by the kinematical requirement

$$\kappa^2 \leq \frac{1-x}{x} z(1-z),$$

which, at the x-values probed at HERA, involves contributions from very small $z \ll 0.1$, where partonic fragmentation functions into hadrons are only poorly $(0.01 < z < 0.1)$ or not at all $(z < 0.01)$ determined from present experimental data. The uncertainty on the fragmentation functions can however be expected to cancel to some extent in the asymmetry, where fragmentation functions appear in numerator and denominator. In our numerical studies below, we are dividing the z-integration in (3) into five bins, in which we compute the asymmetries.

The evaluation of the semi-inclusive DIS cross section (2) contains convolutions over parton distributions inside the target hadron as well as over fragmentation functions for outgoing partons into observed charged hadrons. We use the CTEQ4L [8] leading order parton distribution functions, together with the Binnewies-Kniehl-Kramer (BKK) [9] leading order fragmentation functions. We restrict ourselves to charged hadron production (as also done in all experimental studies at HERA [1] up to now) and approximate the fragmentation function for a parton into a charged hadron by the sum of the fragmentation functions to charged pions and kaons. This approximation yields a satisfactory description of the ZEUS hadron production spectra in [1].

Bin	1	2	3
$\langle Q^2 \rangle/\mathrm{GeV}^2$	6	60	600
$\langle x \rangle$	0.0001	0.001	0.01

Table 1: Kinematical bins used in the neutral current studies.

Bin	1	2	3
$\langle Q^2 \rangle/\mathrm{GeV}^2$	1200	2000	5000
$\langle x \rangle$	0.32	0.32	0.32

Table 2: Kinematical bins used in the charged current studies.

Our evaluations for asymmetries in neutral and charged current (NC and CC) exchanges assume $\sqrt{s} = 300$ GeV and are made for several points in the kinematical (x, Q^2) plane accessible at this centre-of-mass energy. For neutral current hadron production, we evaluate the angular asymmetries in the bins listed in Table 1. These bins all correspond to $y = 2/3$, where the T-odd contributions are kinematically largest. For the evaluation of $\langle \sin\phi \rangle$, we assume the electron beam to be left-handed; a right handed electron beam would result in an asymmetry with opposite sign.

The resulting asymmetries are shown in Figures 1–3. It can be seen that $\langle \cos\phi \rangle$ is typically of the order of a few per cent. For the bins with lower Q^2, one observes that the asymmetry is positive and large for $0.3 < z < 0.9$, while almost vanishing for $0.1 < z < 0.3$. In these z bins, where the perturbative prediction is most reliable, this asymmetry should be easily accessible experimentally. $\langle \cos(2\phi) \rangle$ appears to be of the same order of magnitude and positive for all values of z.

The T-odd asymmetry $\langle \sin\phi \rangle$ does not exceed two per mille in the neutral current case, and attains its largest values at small z, where the fragmentation functions are only poorly known. Given that this asymmetry has to be measured in the presence of $\langle \cos(n\phi) \rangle$-asymmetries, being about an order of magnitude larger, it can only be concluded that the determination of T-odd effects in semi-inclusive DIS is experimentally challenging and requires large luminosity as well as good control over possible systematic effects linking $\langle \cos(n\phi) \rangle$ and $\langle \sin\phi \rangle$. The estimated magnitude of two per mille should also be taken as a reference value to be compared with non-perturbative estimates [2].

The leading order expressions for semi-inclusive hadron production are easily generalized to jet production by replacing the fragmentation functions by a jet definition. At lowest order, each parton can be identified with an observed jet, such that a mere replacement of the fragmentation functions by δ-functions in the energy transfer yields expressions for the 2+1 jet production cross section. Both jets are produced back-to-back and with identical P_T in the centre-of-mass frame of gauge boson and proton, $\langle \cos(n\phi) \rangle$ and $\langle \sin(n\phi) \rangle$ vanish consequently in the integrated jet rate. Only by restricting the final state configuration by cuts on the jet direction, such as suggested for example in [10], we obtain non-vanishing asymmetries, which are comparable in magnitude to the asymmetries obtained for hadron production.

Charged current interactions at HERA result in a final state with an undetected neutrino. Direction and energy of the neutrino can be inferred from the imbalance of momentum in the event, the reconstruction of the kinematical variables is however less precise than in the neutral current case. Charged current interactions are mediated by a massive gauge boson, their magnitude becomes comparable to neutral current interactions only towards large Q^2. Measurements of charged current DIS at HERA can therefore be made only at large Q^2, and the points for our numerical studies have been chosen accordingly. They correspond to bin centres used in recent HERA measurements of the CC cross section, and they are listed in Table 2. In CC interactions, it turns out that the T-odd asymmetries $\langle\sin(n\phi)\rangle$ become kinematically largest for small y, such that we have selected bins corresponding to a minimal value of y.

For CC DIS, one obtains different cross sections for incoming positrons and electrons, since the resulting $W^\pm$ currents couple to different combinations of quark distributions in the target. The cross section for electron scattering is larger than for positron scattering, such that we shall only report on results for asymmetries in electron scattering here; the corresponding asymmetries in positron scattering are smaller in magnitude due to the different sign of parity violating contributions, as demonstrated in [7]. Figures 4–7 represent the azimuthal asymmetries obtained for electron scattering. We observe a pattern similar to the neutral current case: the $\langle\cos(n\phi)\rangle$ asymmetries are both of the order of several per cent, reaching maximum values of about 10% for $\langle\cos(\phi)\rangle$ and 5% for $\langle\cos(2\phi)\rangle$. In charged current DIS, two T-odd asymmetries are present: $\langle\sin\phi\rangle$ and $\langle\sin(2\phi)\rangle$. Both asymmetries are sizable for $z > 0.1$, where the predictions are most reliable. $\langle\sin\phi\rangle$ turns out to be larger than in the neutral current case, and amounts up to one per cent. $\langle\sin(2\phi)\rangle$ is at the level of half a per cent. The ratio between $\langle\cos(n\phi)\rangle$ and $\langle\sin(n\phi)\rangle$ is therefore more favourable in the charged current case, and the $\langle\sin(n\phi)\rangle$ are also larger. Despite the significantly smaller cross section, a measurement of T-odd asymmetries in charged current DIS might therefore be competitive to the measurement in the neutral current case.

In summary, we have investigated the numerical magnitude of various asymmetries in the angular distribution of hadrons in the final state of deep inelastic scattering, as determined by parton model expressions. The resulting estimates for neutral current deep inelastic scattering show that the $\langle\cos(n\phi)\rangle(P_T)$ asymmetries are typically of the order of a few per cent, and should thus be easily measurable. The time-reversal-odd asymmetry $\langle\sin\phi\rangle(P_T)$ does hardly exceed 10^{-3} in neutral current interactions and 10^{-2} in charged current processes, an experimental determination of it is therefore a challenging task. If a substantially larger $\langle\sin\phi\rangle(P_T)$ should be observed at HERA, it would be a clear indication for large non-perturbative T-odd effects, as suggested in the literature [2].

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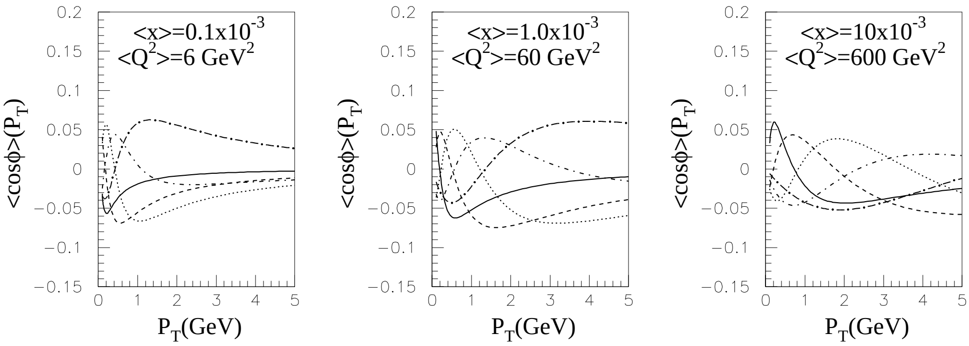

Figure 1: The asymmetry $\langle \cos\phi \rangle (P_T)$ in neutral current charged hadron production. Solid line: $0.005 < z < 0.01$, dashed line: $0.01 < z < 0.05$, dotted line: $0.05 < z < 0.1$, short dot-dashed line: $0.1 < z < 0.3$ and long dot-dashed line $0.3 < z < 0.9$.

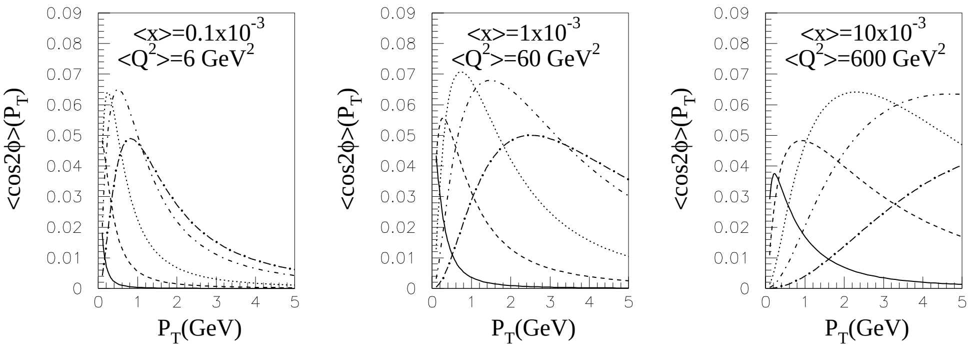

Figure 2: The asymmetry $\langle \cos(2\phi) \rangle (P_T)$ in neutral current charged hadron production. Curves as in Fig. 1.

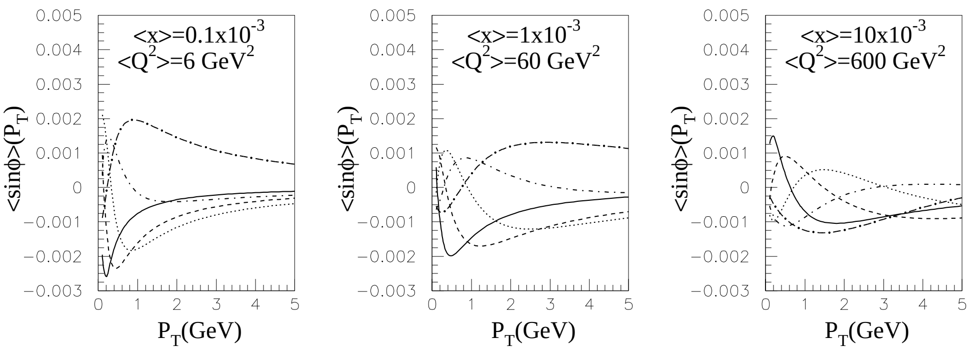

Figure 3: The T-odd asymmetry $\langle \sin\phi \rangle(P_T)$ in neutral current charged hadron production. Curves as in Fig. 1.

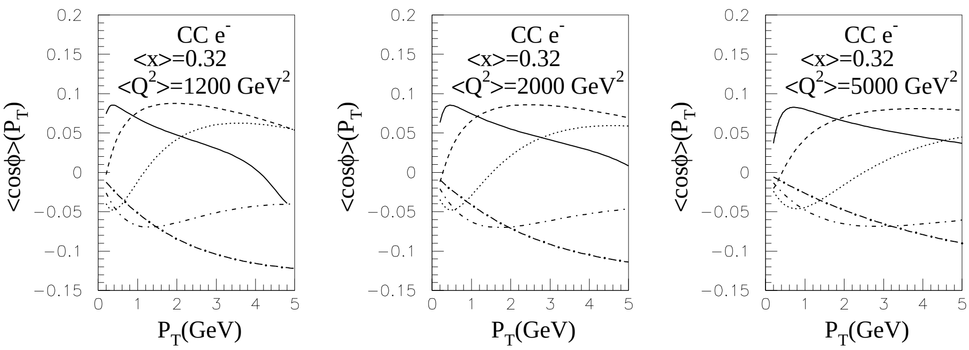

Figure 4: The asymmetry $\langle \cos\phi \rangle(P_T)$ in charged current (e^-) charged hadron production. Curves as in Fig. 1.

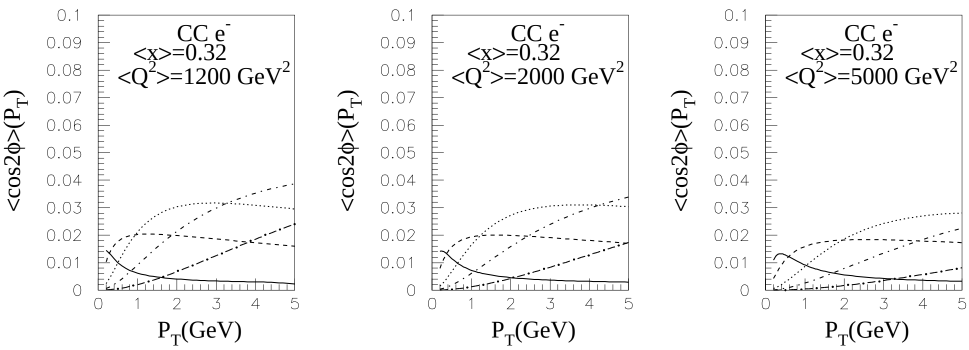

Figure 5: The asymmetry $\langle \cos(2\phi) \rangle(P_T)$ in charged current (e^-) charged hadron production. Curves as in Fig. 1.

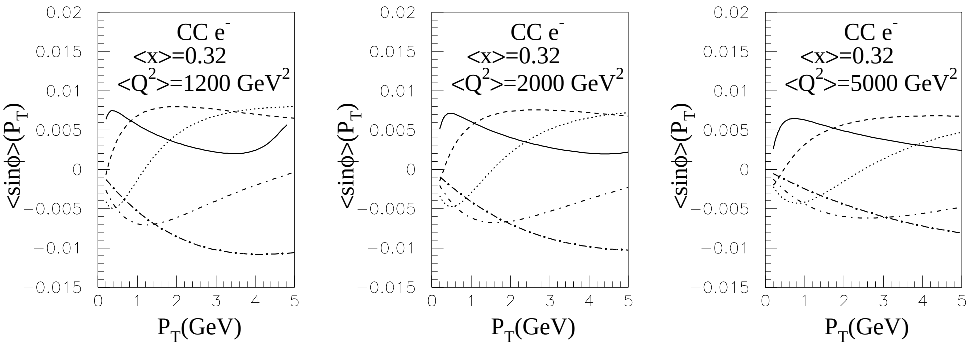

Figure 6: The T-odd asymmetry $\langle \sin\phi \rangle(P_T)$ in charged current (e^-) charged hadron production. Curves as in Fig. 1.

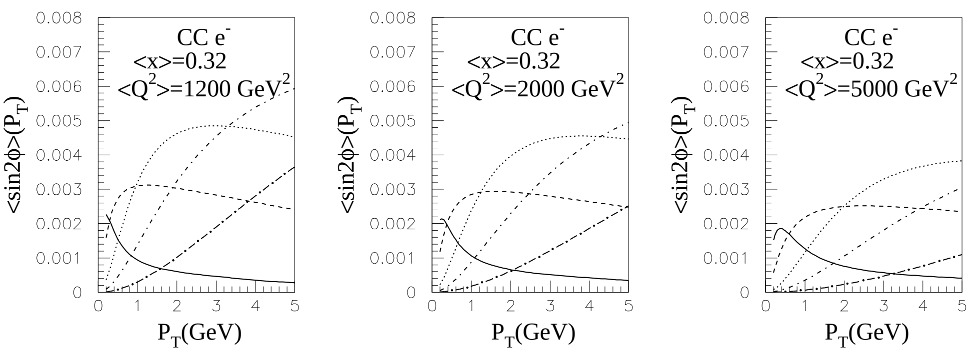

Figure 7: The T-odd asymmetry $\langle \sin(2\phi) \rangle(P_T)$ in charged current (e^-) charged hadron production. Curves as in Fig. 1.